Microgrid Protection using Adaptive Overcurrent Relays
Narendra J. Mahala1 Jignesh B. Pujara2
1M.E. Student 2Assistant Professor
1,2Department of Electrical Engineering
1,2L.D. College of engineering Ahmedabad, India

Abstract— Now day’s microgrid is popular because it can be handle the impacts of Distributed Generators (DGs) and make conventional grids suitable for large scale arrangements of distributed generation. However, the introduction of microgrids brings some challenges. Protection of a microgrid is one of them. Due to the existence of generators at all levels of the distribution system and two operating modes, i.e. Grid Connected and stand-alone modes, the fault currents in a system vary substantially. Consequently, the traditional fixed current relay protection schemes need to be improved. This paper presents a conceptual design of a microgrid protection system which utilizes extensive communication to monitor the microgrid and update relay fault currents according to the variations in the system. This paper also have MATLAB simulation as well as results are presented for both the modes.

Key words: Microgrid, DS (distributed storage), DGs (Distributed Generators), RE (Renewable Energy), PCC (point of common coupling) and IDMT (Inverse Definite Minimum Time)

I. INTRODUCTION
The recent developments in technology and the growing concerns for global warming motivated engineers to search for cleaner and more efficient systems. In order to decrease the impacts of fossil fuel based generation on the environment, the new vision is to generate electricity from cleaner energy sources and closer to the consumption areas. Consequently, the power industry is moving towards Distributed Generation (DG), which may be Renewable Energy (RE) based DG such as wind turbines, solar systems and etc. This also decreases the burden on transmission lines which already operate close to their limits. Although DG has recently become irreversibly popular, there are some serious challenges for the large scale integration to the utility grids. Existing distribution systems are not designed for significant penetration of DG as they were traditionally designed with the assumption of a passive network. The interconnection of RE based DG systems to such networks inevitably changes the characteristics of the system and presents key technical challenges which were previously unknown to grid operators and power engineers [1]. Moreover, DG systems also make contributions to the fault currents around the network. Hence, in case of a fault, the transient Characteristics of the network become completely different [2]. These are only a few of the issues that have arisen in relation with the revolutionary changes occurring in the grids and the way they are operated.

A microgrid is broadly referred to as a well-defined area of an electric distribution network which embeds an appreciable number of distributed energy resources, in addition to local loads, it is managed and controlled by an intelligence and would be capable of operating in isolation from the host utility grid (stand-alone mode of operation), as well as in conjunction with the grid (grid-connected mode of operation). A microgrid can be a residential neighborhood, an industrial or commercial facility, a university campus, a hospital, an off-grid remote community, etc. The microgrid could be forced to switch to the stand-alone mode of operation, for example, due to the occurrence of a fault in the host grid, or it could intentionally disconnect itself from the grid, for example, if economics warrant the stand-alone connected mode of operation). A microgrid can be a residential neighborhood, an industrial or commercial facility, a university campus, a hospital, an off-grid remote community, etc. The microgrid could be forced to switch to the stand-alone mode of operation, for example, due to the occurrence of a fault in the host grid, or it could intentionally disconnect itself from the grid, for example, if economics warrant the stand-alone mode of operation [2]. Regardless, the microgrid is expected to ensure efficient service to the microgrid loads, with superior quality and reliability, in addition to economical benefit for the microgrid owner, as well as ancillary services to the host grid.

The organization of this paper is as follows: Section II Architecture of microgrid, Section III Challenges associated with the microgrid protection, Section IV microgrid protection section V Case study, section VI Adaptive overcurrent relay; section VII Matlab simulation and results and Section VIII draws the conclusion.

II. ARCHITECTURE OF MICROGRID
The main components of a microgrid are distributed generators (wind turbines, photovoltaic arrays, rotating machines, fuel cells, etc.), distributed energy storage devices (flywheels, batteries, super capacitors, compressed-air systems, etc.), and local critical/noncritical loads. Distributed Generators (DGs) can generally be classified into two main groups, based on their interfacing media: (i) traditional rotating-machine-based DGs and (ii) electronically interfaced DGs. The first group are those that consist of direct-coupled rotating machines and are directly interfaced to the network through interconnection transformers (e.g., a synchronous generator driven by a reciprocating engine or an induction generator driven by a fixed-speed wind turbine). The second group, however, utilizes DC/AC or AC/DC/AC power-electronic converters as their coupling media with the host grid (e.g. photovoltaic systems or variable-speed wind energy conversion systems). The control techniques and characteristics of power-electronic converters are significantly different than those of the conventional rotating machines. Moreover, due to the limited current rating of silicon devices, the fault current of electronically interfaced DGs should be limited to a maximum of about two times their nominal current.

Figure 1 shows a microgrid schematic diagram. The microgrid encompasses a portion of an electric power distribution system that is located downstream of the distribution substation, and it includes a variety of DER units and different types of end users of electricity and/or heat. DER units include both distributed generation (DG) and distributed storage (DS) units with different capacities and...
characteristics. The electrical connection point of the microgrid to the utility system, at the low-voltage bus of the substation transformer, constitutes the microgrid point of common coupling (PCC). The microgrid serves a variety of customers, e.g., residential buildings, commercial entities, and industrial parks [2].

Fig. 1: Architecture of a microgrid

A microgrid of Figure 1 normally operates in a grid-connected mode through the substation transformer. However, it is also expected to provide sufficient generation capacity, controls, and operational strategies to supply at least a portion of the load after being disconnected from the distribution system at the PCC and remain operational as an autonomous (stand-alone) entity [2]. The existing power utility practice often does not permit accidental islanding and automatic resynchronization of a microgrid, primarily due to the human and equipment safety concerns. However, the high amount of penetration of DER units potentially necessitates provisions for both stand-alone and grid-connected modes of operations and smooth transition between the two (i.e., islanding and synchronization transients) to enable the best utilization of the microgrid resources.

III. CHALLENGES ASSOCIATED WITH THE MICROGRID PROTECTION

Traditionally, distribution networks have been designed to operate radially, that is, the power flows from the upper voltage levels down to the customers connected to radial feeders. This simple configuration has enabled straightforward protection strategies for typical distribution systems. Thus, the conventional distribution networks are protected by such simple protective devices as fuses, reclosers, and overcurrent relays. The practice of operating microgrids, however, disturbs the traditional protection strategies which are based on the assumption of a radial network structure featuring large fault currents and unidirectional power flows. The protection scheme of a microgrid must ensure safe operation of the microgrid in both modes of operation. Therefore, the protection issues associated with each mode of operation should separately be addressed by the protection algorithm. In the following subsections, the traditional protection of typical distribution systems will first be reviewed, then the challenges associated with the microgrid protection are briefly introduced.

A. Traditional Protection Coordination:

Overcurrent protective devices, most commonly fuses, reclosers and inverse-time overcurrent relays, are employed for the protection of traditional distribution networks. In a feeder, fuses must be coordinated with the recloser installed at the beginning or middle of the feeder. The coordination means that a fuse must operate only if a permanent fault impacts the feeder (fuse-saving scheme). For a temporary fault, however, the recloser must rapidly open (fast mode) to isolate the feeder and give the fault a chance to self-clear. If the fuse fails to operate for a permanent fault, the recloser will back it up by operating in its slow mode. The feeder relay will operate lastly only if both the recloser and the fuse fail [1] [2].

B. Grid-Connected-Mode Protection:

In the grid-connected mode, fault currents are fairly large due to the contribution of the host grid and, thus, the employment of conventional overcurrent relays is possible. However, due to the existence of DERs, the radial structure of the networks is compromised, and protection coordination may be affected, or entirely lost in some cases. Addition of a DER to a radial feeder anywhere downstream of the feeder recloser may (i) change the minimum and maximum fault current of the feeder, (ii) decrease the fault current of an upstream protective device as compared to that of downstream devices, and (iii) result in a bidirectional power flow. Thus, depending on the DER type, DER location and DER size, several issues may arise in the grid-connected mode of operation.

The main protection issues associated with the introduction of DERs to a distribution network include (1) blinding of protection (2) false/sympathetic tripping (3) recloser-fuse miscoordination (4) fuse-fuse miscoordination (5) failed auto-reclosing.

C. Stand-Alone Mode Protection:

Power-electronic converters should be protected against overcurrent conditions, as their switches have limited current ratings. This, in turn, results in the limited fault current capability of EC-DERs. Therefore, fault currents are relatively small in the stand-alone mode of operation, as compared to those experienced in the grid-connected mode of operation. Moreover, depending on the ratio of the power generated by rotating-machine-based DERs to the power generated by EC-DERs, the fault current magnitude can vary over a fairly wide range in a stand-alone microgrid.

Consequently, the conventional overcurrent protection schemes are no longer adequate for the stand-alone mode of operation [4]. In addition, under voltage protection functions may fail to detect all types of faults, as a fault might include a significant resistance. Therefore, there is a need to have a fresh look into the fundamentals of relaying to come up with a protection scheme capable of responding appropriately to different types of faults within an stand-alone microgrid.

IV. ADAPTIVE PROTECTION FOR MICROGRID

The principles to be used to develop the adaptive overcurrent relaying scheme for a given microgrid. As mentioned before a microgrid has two modes of operation, the isolated mode and the grid-connected mode. This creates the need for an adaptive relaying scheme. This scheme will have the ability to adapt to and operate in both of the microgrid’s modes of
operation. The relays in the scheme will change their settings automatically by detecting the grid’s mode of operation. This is not the only way to effectively protect a microgrid, but it is an effective and novel manner, which can be implemented in future grids.

The protection elements required are the same as the ones used in a conventional grid, namely, transducer, circuit breaker and relays. The only specificity is that the relays have to be microprocessor based digital relays with adaptive capabilities. The overcurrent relaying method uses the overall impedance of the system to calculate the current through it, if the impedance is too low and the current too high, in other words a fault is present, it will trigger the circuit breaker to open and isolate the fault. In the two modes of operation the overall impedance of the power system consisting of the microgrid and utility grid will vary. The fault level of the network and the magnitude of the fault current may reduce immensely when a microgrid changes from grid connected mode to isolated mode. This might lead to reduced sensitivity of the overcurrent relays set to operate for high fault currents under the grid connected mode of operation. Therefore it is important that the relays are communicated with and informed of what mode of operation the microgrid is in, otherwise it may trip unnecessarily [6].

This development is based on the requirements of the microgrid protection. It will be based on the technique of linear programming, where the network’s current will enter the relay. The relays will react according to the entered current, based on a fixed Time Multiplier, Pick-up current and Normal Inverse characteristic. The development will suit the protection requirements for a microgrid. The relays in the power network will be coordinated in such a manner that the breaker closest to the fault will open first. The circuit breakers further away from the fault will open later and only if necessary.

A. Challenges faced in adaptive relaying:
The main challenge faced while implementing adaptive relaying is changing the relay settings to suit the load, generation level and topology changes. Overcoming this challenge is what makes this type of relaying effective. When implementing directional overcurrent relaying, coordination of relays is particularly difficult in multi-loop and multi-source networks. This is because current flows through the network in different directions to reach the loads. These are usually three different methods used to reach coordination of relays. These methods are trial and error method, topological analysis method and optimization where the parameters of the relay are set in a manner to optimize the protection of the grid [1].

B. Adaptive Overcurrent Relaying Scheme:
It is considered that the protection elements required are the same as the ones used in conventional grid. The only specificity is that the relays have to be microprocessor based digital relays with adaptive capabilities. The protection method used is overcurrent relaying. The protection elements required are the same as the ones used in a conventional grid, namely, transducer, circuit breaker and relays. The overcurrent relaying method uses the overall impedance of the system to calculate the current through it, if the impedance is too low and the current too high, in other words a fault is present, it will trigger the circuit breaker to open and isolate the fault. In the two modes of operation the overall impedance of the power system consisting of the microgrid and utility grid will vary. The fault level of the network and the magnitude of the fault current may reduce immensely when a microgrid changes from grid connected mode to isolated mode. This might lead to reduced sensitivity of the overcurrent relays set to operate for high fault currents under the grid connected mode of operation. Therefore it is important that the relays are communicated with and informed of what mode of operation the microgrid is in, otherwise it may trip unnecessarily [4] [6].

C. IDMT Relay Characteristics:
There are various valid characteristic functions for overcurrent relays, for its ease of simulation the IEEE standard is used throughout this research. This function is also useful because it enables the user to approach the coordination problem as a linear programming problem. The function is described in Equation (1).

\[
t = \frac{\text{Current Transformer Ratio}}{\text{Plug Setting}} - 1
\]

Where:
- \( t \) = Trip time;
- \( TM \) = Time multiplier;
- \( PS \) = Plug Setting;
- \( \text{CT ratio} \) = Current Transformer Ratio;

The above function represents the normal inverse IDMT function. This is used because it provides fast operating times and is effectively used for coordination.

As mentioned previously, power system protection operates through two different subsystems. These subsystems are the primary protection and the back-up protection. For the protection system to be effective these two subsystems have to be coordinated as suggested in Figure 2. In Figure 2 there are two Time vs. Current curves, \( t_b \) for the backup relay and \( t_p \) for the primary protection relay. In between these two curves are arrows labelled CTI, which stands for Coordination Time Interval. CTI is the time between the operations of the two relays for the same fault [4]. This relationship can be described as follows:

\[
(F1) - (F1) \geq \text{CTI} \quad (2)
\]

\[
(F2) - (F2) \geq \text{CTI} \quad (3)
\]

V. CASE STUDY
The test microgrid and utility system is shown in fig.3. The utility generation is available at a voltage of 69kV which is then stepped down to 13.8kV by the utility’s 69kV/13.8kV two winding transformer. Both DGs produce a voltage of 13.8 kV which is also the rated voltage for supplying the value is chosen because distributed generators in microgrids normally have a capacity less than 10MVA[1].
Fig. 2: Test model.

Buses 1, 2 and 5 belong to the microgrid while buses 3 and 4 belong to the utility. Bus 4 is connected to bus 5 at the PCC through a static switch (SS). In stand-alone mode SS is open; DG1 and DG2 supply the entire microgrid load as load 1 at bus 1 and load 2 at bus 2, utility supplies load 3 at bus 3 separately[1] [5].

In grid connected mode SS is closed after synchronizing DG1, DG2 with the main generator. Loads 1, 2 and 3 are shared altogether by all the generators.

The circuit breakers connected to buses 1 and 2 are used to isolate faults that may occur in the microgrid. These are controlled by relay 1 and 2 respectively. Relay 3 is used to isolate any faults that may occur close to load 3 be it within the microgrid or in utility.

VI. ADAPTIVE OVERCURRENT RELAY MODEL

The relay model is designed based on the IEC normal inverse IDMT overcurrent relay equation (1) [3] [7].

Fig.3 shows simulation model of adaptive overcurrent relay for the microgrid.

The Model works as follows:

1) Through the input (1), it receives a phase current signal from phase A of the power system.
2) The RMS value of the current is then calculated using the RSM block. Which is set to 50Hz.
3) The zero order hold block is used as a sampler. It has a sampling rate of 0.1s.
4) Then the signal goes through an “IF” block. This block determines which mode of operation the microgrid is in. If the current value ranges from 200A to 4000A it is assumed that a fault in stand-alone mode has occurred. If the current ranges from 4000A to 10000A it is assumed that a fault in the grid connected mode has occurred.

5) If the system is in grid connected mode the signal is transferred to the first Relay and Fun block, if it is in stand-alone mode of operation the signal is sent to the second Relay1 and Fun block.
6) Once the signal has reached either “Relay” or “Relay1”, these block determines whether the current is above the nominal current or not. If it happens to be above the nominal there is a fault, these blocks will output signal of value 1.
7) Fun block and Relay1 will determine the time delay by comparing the fault current to the value placed in a table in the blocks. The IDMT curves for grid connected mode are shown in Fig. 5 and the stand-alone mode are shown in Fig.6.
8) The combination of two blocks Relay and Fun block works together to generate a time delayed trip signal.
9) Add and Gain blocks are used to invert the produced signal so that it can be recognized by the circuit breaker which receives the signal. The 3-phase circuit breaker opens when a signal of value 0 is sent to it [4] [7].

Fig. 3: flow diagram of Adaptive overcurrent relay

Fig. 4: Simulation model of adaptive relay.
VII. MATLAB SIMULATION AND RESULTS

A. Simulation Model Of A Microgrid:

Fig. 7: Simulation model

Fig.7 shows simulation model of microgrid. Two test cases Test 1 to 4 have been carried out to test and validate the performance of the adaptive relaying scheme. The test cases are described as below:

Test 1: Fault in microgrid side while in stand-alone mode
Test 2: Fault in microgrid side while in grid connected mode
Test 3: Fault in Utility side while in stand-alone mode
Test 4: Fault on Utility side while in grid-connected mode

B. Simulation Results:

1) Test 1: Fault in microgrid side while in stand-alone mode:

Fig. 8: fault current waveform

In Test 1, the microgrid is operating in stand-alone mode with SS open. The 3-phase to ground fault occurs at point A as shown in Fig.3 at time t=0.1s from the start of simulation. Relays R1 and R2 sees fault current fed to the fault from DG2. R1 and R2 here operate according to curves shown in Fig.6 and parameters of Table 1 and Table 2 respectively. The coordination between R1 and R2 is such that R1 operates first and isolates its circuit breaker connecting DG1 to Bus 1. Fault current is calculated to be 1110A for which operating times for R1 and R2 calculated from Equation (1) are 0.32s and 0.41s respectively. However, Fig. 8 shows that the trip signal comes only 0.35 seconds after the fault inception.

2) Test 2: Fault on microgrid side while in grid-connected mode:

Fig. 9: fault current waveform

In Test 2, the microgrid is operating in stand-alone mode with SS close. The 3-phase to ground fault occurs at point A as shown in Fig.3 at time t=0.1s from the start of simulation. Relays R1 and R2 sees fault current fed to the fault from DG2. R1 and R2 here operate according to curves shown in Fig.5 and parameters of Table 1 and Table 3 respectively. The coordination between R1 and R2 is such that R1 operates first and isolates its circuit breaker connecting DG1 to Bus 1. Fault current is calculated to be 7430A for which operating times for R1 and R2 calculated from Equation (1) are 0.35s and 0.41s respectively. However, Fig. 9 shows that the trip signal comes only 0.38 seconds after the fault inception.

3) Test 3: Fault on Utility side while in stand-alone mode:
The relay model used in this simulation is based on the functionality of digital relays, digital relays have options such as mode of operation. This additional function was used to develop the relay model used in this paper. The relay’s ability to operate in different modes is makes it effective in adaptive relaying.

IX. APPENDIX

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<tr>
<th>Grid-connected mode</th>
<th>Stand-alone mode</th>
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<td>CT ratio</td>
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<tr>
<td>TM</td>
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<td>PS</td>
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Table 1: Relay 1 parameter

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Table 2: Relay 2 parameter

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Table 3: Relay 3 parameter

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